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THE NATURE AND CONTROL OF SNOW CORNICES ON THE BRIDGER RANGE SOUTHWESTERN MONTANA

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INTRODUCTION

Prevailing westerly winds create large snow cornices along the lee crest of the Bridger Range in Southwestern Montana. Studies during the winters of 1965-68 revealed some of the mechanics of cornice accumulation and deformation and showed that cornices may be controlled by wind deflecting structures. The study site averages 8500 ft. (2590 m.) A.S.L. and extends a linear distance of one half mile (0.8km.) at the head of the Maynard Creek watershed. Prevailing winds are from the west, or approximately perpendicular to the Bridger ridgeline. Maximum wind speeds occasionally exceed 100 mph (44.7 mps).

Since a high proportion of naturally triggered avalanches in many recreation areas are caused by cornice collapse, prevention or control of these features is of importance where recreational safety is of primary importance.

To a large extent, this paper is an embellishment of the excellent pioneer writings of Welzenbach (1930), and Seligman (1936), and the unwritten ideas of that master mountaineer, Andre Roch.

DEFINITION

For purposes of clarity, a cornice (German "Wachte") is defined as a projection of snow formed by wind deposition to the lee of a ridgeline or slope inflection. A typical composite cornice is illustrated in Fig. 1.

STORED WATER

The declivity of lee slopes controls the size of cornices developed upon them, hence the amount of water that is available from cornice snow.

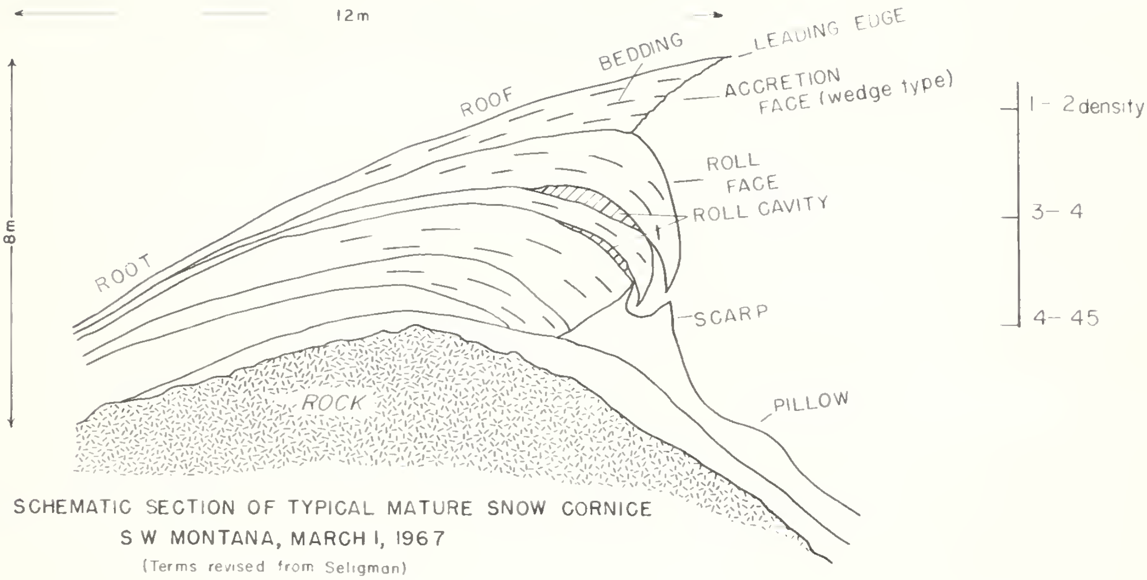

FIG. 1 SCHEMATIC SECTION OF TYPICAL MATURE SNOW CORNICE
S W MONTANA, MARCH 1, 1967
(Terms revised from Seligman)

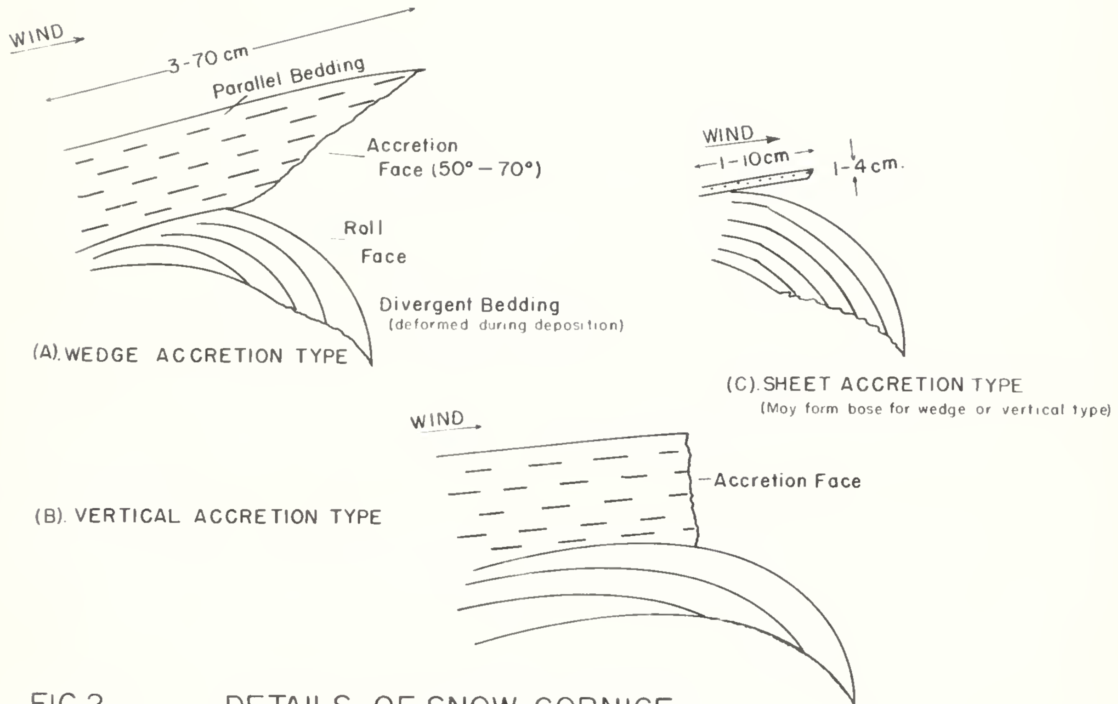

FIG. 2 DETAILS OF SNOW CORNICE ACCRETION ZONES

The lee slopes on the Bridger Range average about 35° in inclination. On such slopes, maximum vertical thicknesses of cornices in late winter measure about 10 m. These cornices correspondingly extend upward and outward from the ridgeline as much as 15 m. (Fig. 3a). If the slopes are steeper than 35°, the horizontal component of development is limited because there is less support along the lee slope line.

On 35° lee slopes, measurements made April 2, 1967, indicate that approximately 54 acre feet (67,688 m^3) of water was contained within the cornice masses along the 2.5 km crestline above the Maynard Creek watershed (Fig. 6). This amounted to about one percent of the total equivalent water estimated to have been stored in the watershed at that time.

CORNICE MECHANICS

Wedge and Sheet Cornice Growth. Several processes may contribute to cornice growth. The most common type of growth is caused by the downwind accretion of snow particles in progressive outward and upward extending layers. The process forms a wedge shaped mass along the leading edge. As a variation to the wedge type growth, under conditions of particularly effective grain to grain adhesion and copious supply of stellar flakes, a horizontal sheet of snow only a few cm. thick may extend as much as 10 cm. into space (Fig. 2C). These sheets or wedges may eventually collapse or sluff off their own weight, may stiffen to form the base on which succeeding layers build, or may curl downward plastically under the influence of gravity. In the wedge type, the accretion face (Fig. 1) has an underslope that slants inward toward the main cornice mass at an initial angle of about 55°. When the wedge is deformed, as it usually is, the angle of the accretion face changes, of course.

When conditions are not favorable for wedge accretion, the cornice roof can often build upwards but without horizontal extension. In this case, the accretion face (Fig. 2B) remains approximately vertical.

Clinging Mechanism. Photos indicate wedge accretion (Fig. 2A) to be most commonly brought about by the mechanical clinging of either rimed or unrimed new stellar snow flakes under a wide range of temperature, wind, and humidity. The crystalline appendages can adhere mechanically to one another along the leading edge until sintering takes place and hardens the mass. Seligman (1936) believed this was the only mechanism which could account for horizontal growth of cornices.

Granular Cornice Growth. Although wedge accretion most commonly forms from stellar snow, macro photographs taken of granular snow during cornice growth suggest that this form of snow can also cause wedge accretion. The latter type of growth has been observed only during conditions of high relative humidity, slightly below freezing temperatures, and moderate surface wind speeds of from 15 to 35 mph (7 - 15 m./sec.). Although very difficult to measure quantitatively, rounded saltating grains apparently adhere and sinter nearly instantaneously at the tip of the leading edge. The edge is thus extended particle by particle outward and upward. The mechanism for this very rapid sintering process is unclear at present.

Discussion of Adhesion Causes. It is possible that riming and electrostatic effects are important in grain adhesion prior to sintering. However, it should be noted that wedge growth by accretion of granular particles has been observed both on clear days and on days when riming was occuring.

Other possible mechanisms to explain such adhesion and rapid sintering are now under study. These include the measurement of possible

temperature drop due to wind diffusion near the cornice edge and the inspection of grains for free water coating.

Densities in the forming cornice wedge may range from 0.1 $g/cm.^3$ for the clinging stellar snow types to 0.25 $g/cm.^3$ for the sintered granular type.

If humidity, temperature, and snow conditions are favorable, cornices can build under relatively low wind speeds (about 16 mph or 7 mps). Naturally, a source for the snow supplied to the leading edge is a prerequisite. Often the only such source is the root of the cornice itself, which tends to scour as the leading edge extends. Ordinarily, winds above 60 mph (27 mps) will scour the entire cornice surface and abruptly reduce its height.

CORNICE DEFORMATION

Several types of deformation may take place within the cornice mass. Gravity is primarily responsible in all cases. Qualitatively, it has been observed that deformation of the growing edge is accelerated under near freezing conditions because of the increased plasticity of snow.

Roll Cavity. A critical aspect of deformation is the downward folding ("involution" of Seligman 1936) of the accretion wedge to form a curved tongue which usually encloses an air space beneath and behind it (Fig. 1). We have named this air space the "roll cavity". Folding may well exceed 90° and is brought about by intergranular adjustment. The weakness zone thus created may be several feet in both height and width, depending upon the geometry of the original wedge and the amount of folding which has taken place. Since the roll cavity tends to persist, at least in compressed form, it remains a weakness zone within the cornice mass that tends to localize future fractures. These zones can be exploited when

dynamiting cornices for control purposes. Using time-lapse photography, we were able to demonstrate that some deformation is contemporaneous with cornice growth. When this happens, the bedding layers in the accretion wedge tend to diverge toward the upper and outer edge. Slightly below freezing temperatures seem to be prerequisite for such contemporaneous deformation to occur.

<u>Bedding</u>. Under relatively cold conditions, contemporaneous deformation is minimal and divergent bedding does not form during accretion. Thus, by analyzing the nature of the bedding, it is possible to estimate the temperature conditions under which the cornice wedge formed.

Welzenbach and Paulke (1928) originally had observed that involution of the growth wedge could be contemporaneous with deposition, as described above. They suggested that the amount and rate of deformation depended upon the infiltration of water in the cornice. To date, no relation between rate of deformation and infiltration of water has been noted on Bridger Ridge. It is hoped that experiments with dyes may indicate the true nature of intergranular movement involved with cornice deformation.

<u>Creep and Glide</u>. The entire cornice mass creeps and/or glides continuously. Such movement is well known for snow in general (see, for instance, in der Gand and Zupančič, 1965). As creep or glide progresses, tension fractures tend to develop between the cornice mass and ridgeline bedrock. During the winter of 1967-68 at Bridger Ridge, the cornice root moved away from the ridgeline leaving a tension fracture 1 m. in width near the surface. Bits of bedrock embedded in the icy wall of the cornice mass proved that the wall was once in contact with the rock.

In order to determine the nature of deformation within the main cornice mass, vertical rods emplaced in the cornice roof behind the

leading edge were observed over a period of several weeks. As in typical snow creep, the rods were tilted as much as 30° from the vertical (downhill) within 9 days. Similarly, strata marked with spray paint and originally having 14° westward inclinations, were tilted 20° eastward after 9 days of observation. Thus, the entire cornice mass tends to roll downward in time. It should be emphasized that this type of deformation takes place within the solid part of the cornice and is independent of the more rapid deformation of the unsupported accretionary wedge described above.

WIND DATA

Anemometers were placed parallel to the wind direction and 35 cm. above the snow surface on a cornice roof that was slightly convex upward. It was found that the wind speed was reduced several percent toward the leading edge of the cornice. This phenomenon had previously been noted by Seligman (1936) and probably results from the divergence of air moving over the convex surface. Parenthetically, it may be stated that a convex cornice roof is usually the result of deformation.

An abrupt reduction in wind speed takes place below and to the lee of the leading edge. Here, in spite of high winds above the cornice roof, significant vertical vortices of the type postulated by Welzenbach (1930) do not develop. This conclusion was reached after observing that soap bubbles released in the space beneath the leading edge of the cornice exhibited only a slow drifting motion when high winds were blowing above. Likewise, overshot snow sifting through this zone tends to fall to the base of the cornice face. Snow does not significantly plaster to the face unless blown by eddy currents that flow through gaps in the cornices.

"Suction Cornices". The idea of a "suction cornice" originated with Welzenbach (1930). He postulated that the vertical vortices

mentioned above could hollow out the space beneath the accretionary wedge and could help extend the leading edge by deposition from below. This idea was refuted by Seligman (1936) who also concluded that the vertical vortices were not strong enough to significantly influence cornice growth. Nevertheless, Seligman applied the term "suction cornice" when discussing the building of cornices from stellar flakes that cling together along the leading edge below the air stream.

"Pressure Cornice". Seligman also retained Welzenbach's term, "pressure cornice" to describe the wind-packed snow that is built into the air stream along the cornice roof, there to be hardened by sintering. Because neither "suction" nor "pressure" accurately suggest the nature of cornice accretion, it seems advisable to abandon these terms in future usage.

Other Terms. We recommend retaining the term, "scarp" for the steep-fronted drift that builds along the lower cornice face by the fall of over-snow snow (Fig. 1) and we also recommend retaining the term, "snow cushion" or "pillow" for the low drift that connects the scarp with the undisturbed snow of the lee slope.

CORNICE CONTROL STRUCTURES

M. André Roch (personal comm. 1967) was among the first to propose wind deflecting baffles for modification or prevention of cornices. The device which we have found to be most effective is a panel mounted on vertical supports on the ridge top and inclined with higher end toward the prevailing wind. These have been variously called "pupitre", Düsendächer, "toits", "blower roofs", or "jet roofs".

Although the work of the Austrians, Hopf and Bernard (1963), brought out several important principles in the use of jet roofs, we felt further observation of these structures was necessary because they had never been

Figure 3a - Summit of Bridger Range, Montana, showing cornice study area and typical cornice-forming conditions.

Figure 3b - Jet roof on Bridger Range, showing furrow in cornice.

tested in the climate of the Northern Rockies. Also, the dynamics of airflow through them had not been analyzed. We concur that jet roofs are effective in preventing cornices. To date, ten of these have been built on Bridger Ridge incorporating various designs, inclinations, and materials. Some general conclusions are as follows:

(1) If single jet roof panels are to be erected, an efficient arrangement is to use solid 8 x 10 ft. (2.4 x 3 m) frames mounted on two upright posts by means of pivot bolts. These structures are guyed to the ground using no. 9 gauge wire and 4 ft. (1 m) cement rebar anchor pins. No holes need to be dug, and the structure is stable on solid rock provided both uprights and panel ends are guyed. One of these can be assembled and erected by two men in approximately four hours. Present cost of materials (Bozeman, Montana) is about $25.00 per unit.

(2) Jet roofs of the above dimension can be effectively mounted on four posts but assembly and erection are much more difficult than in the case of the two posted model.

(3) If multiple jet roofs are to be erected along a ridge, the space between them should be no wider than the width of the panel (also noted by Hopf and Bernard, 1963).

(4) Jet roofs consisting of panels with open slats have proved slightly less effective than the solid type. The former have the advantage of preventing buildup of snow on the panel, and naturally less material is involved. Although such snow accumulation was not found to be a problem in the Bridger Range

environment, it could be serious in areas of heavy wet snows and less frequent strong winds.

(5) Jet roofs should be erected where sufficient wind is available to keep them operable; otherwise, they may become filled or covered with drifted snow. The weight of the snow thus accumulated could distort or break the jet roof.

(6) The most efficient inclination for the jet roof is that which approximates the angle of the lee slope. This confirms similar conclusions by Hopf and Bernard, (1963), but further discussion of this aspect is given below. Note that throughout this paper the angle of inclination referred to is measured with respect to the horizontal plane.

Jet Roof Inclinations. For experimental purposes on Bridger Ridge, a jet roof was inclined at 40°, an angle deemed too steep for efficient operation over the 30° slope. A sharp cup-shaped hollow developed in the snow to the lee of the structure, but a secondary cornice accumulated beyond the hollow. By comparison, an adjacent jet roof inclined 25° was distinctly superior. The roof at 25° produced a long furrow completely eliminating the cornice on the lee slope.

Steeply inclined jet roofs can be used, however, in conjunction with very steep or vertical lee slopes, for above these slopes there is insufficient support for extensive horizontal cornice development to occur even if jet roofs were not used. Dangerous cornices can develop over such steep slopes if not controlled, for considerable vertical accumulation without horizontal extension is common.

Model Experiments. In order to better understand the dynamics of jet roof action, a full-sized jet roof was erected on a level field

SNOW PROFILES SHOWING
JET ROOF ACTION
BRIDGER RANGE, MONTANA
1966-1967

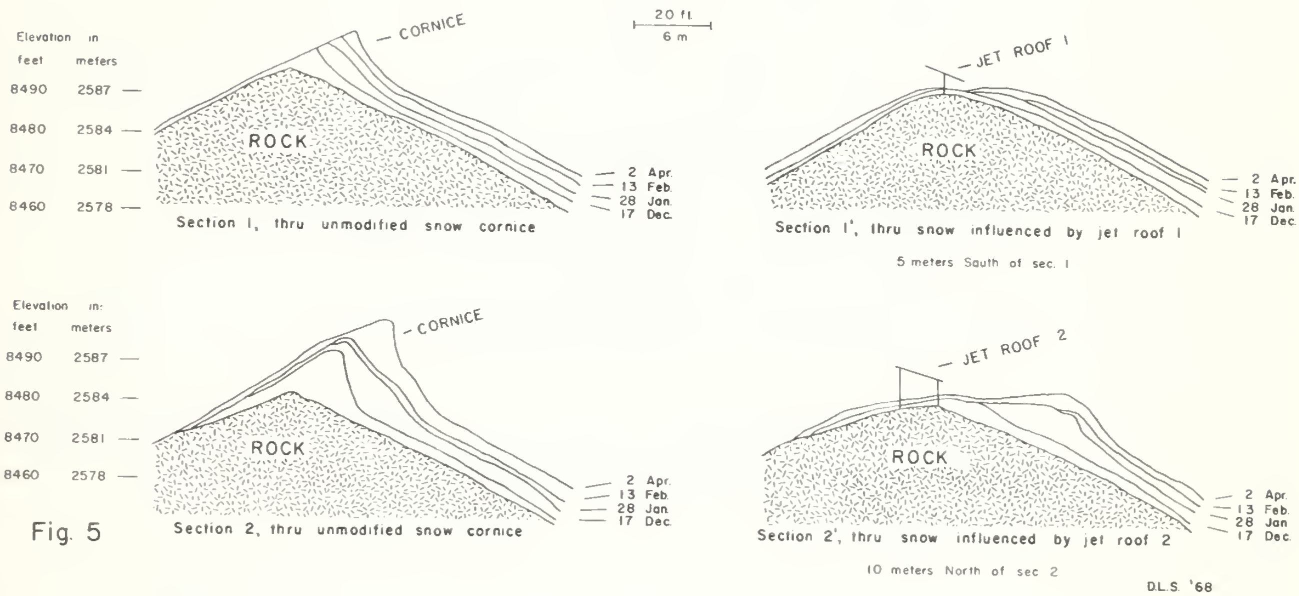

Fig. 5

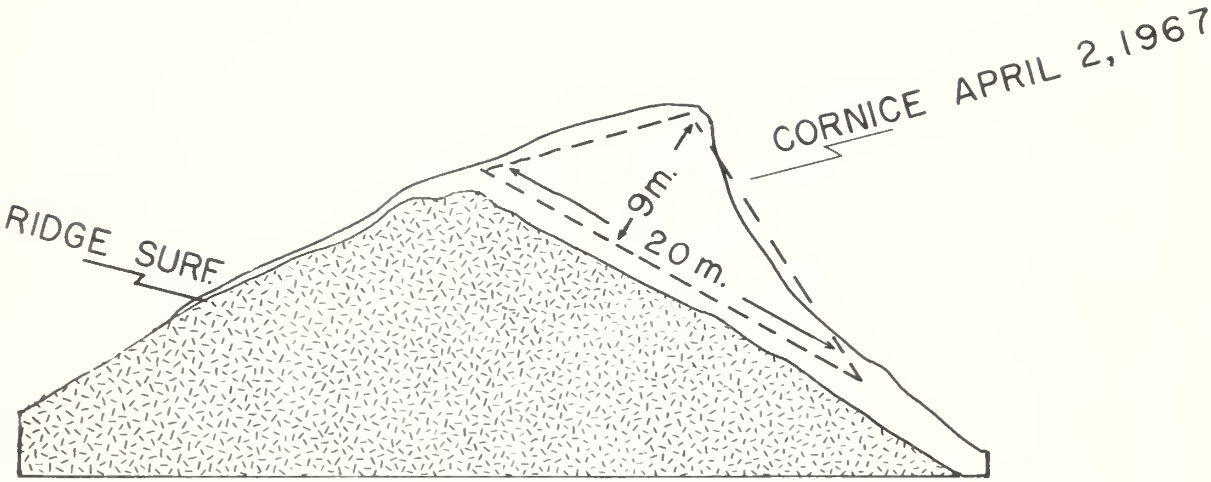

FIG. 6 WATER STORED IN SNOW CORNICE ABOVE MAYNARD CREEK WATERSHED ON BRIDGER RANGE, MONTANA

Kilometers at ridge top 2.5

Average density of cornice .30

Cubic meters of stored water 6,7688

Acre feet of stored water 54.3

which was not snow covered. Anemometers were mounted with cups 43 cm. above ground level at 4.5 m upwind, and at 4.5 and 9 m downwind from the center of the jet roof. Wind speed measurements were made for jet roof inclination angles from 10^{o} through 80^{o} from the horizontal. The results of these measurements are given in Table 1. As can be seen, downwind acceleration of the air is maximized with inclination angles between 10^{o} and 20^{o}. Although the measurements indicate a decrease in wind speed for roof angles greater than 30^{o}, in actual use angles greater than 30^{o} can be used on ridges which have correspondingly steep lee slopes. In order to reconcile the apparent contradictions of the effectiveness of steep roof angles with the reduced downwind velocity, a short series of wind tunnel experiments were made using a laboratory scale of the jet roof.

The model used was a 1:48 scale of the field jet roof. Measurements of the percent increase or decrease in the wind speed downwind of the laboratory model jet roof were made at approach speeds of approximately 7, 6, 3.8, and 1.9 m/sec. Changes in mean wind speed at the approach position did not produce a consistent downwind effect beyond the jet roof although there was some variation in the relative changes. The results of the model study given in Table 2 agree roughly with the results which were obtained in the full scale tests for the same relative positions of the anemometers.

In addition to comparing the wind speed in the laboratory model with wind speed in field tests (at the same relative positions), measurements were made at several other positions downwind of the laboratory model jet roof. Specifically, the speed at the lee edge of the model roof was found to be increased by approximately 10, 15,

TABLE 1. EFFECTS OF "JET ROOF" ON WINDS BLOWING OVER BARE LEVEL GROUND

(Undisturbed wind speeds, with which these are compared, were recorded 4.5 m upwind from the model jet roof)

Inclination of jet roof	Per Cent Change of Wind Speed	
	4.5 m to lee of jet roof	9 m to lee of jet roof
10°	10%	12%
20°	6%	12%
30°	-7%	-1%
40°	-30%	-20%
50°	-37%	-33%
60°	-35%	-28%
70°	-44%	-23%
80°	-56%	-33%

Note: Each percentage change represents the mean of our ten minute measurement periods for each angle of inclination. From 50° to 80°, 35 cm was removed from the lower edge of the jet roof in order to prevent a complete wind block beneath the panel. Such a design is commonly in use (Kolktafel mit Bodenspalt, Hopf and Bernard, 1963) and is demonstrably effective in causing scour and in hardening the scour surface and resulting horseshoe-shaped drift to leeward.

Since frictional drag (shearing stress) varies with approximately the square of the wind speed, a 10% increase in wind speed represents about a 20% increase in frictional drag (increased scour).

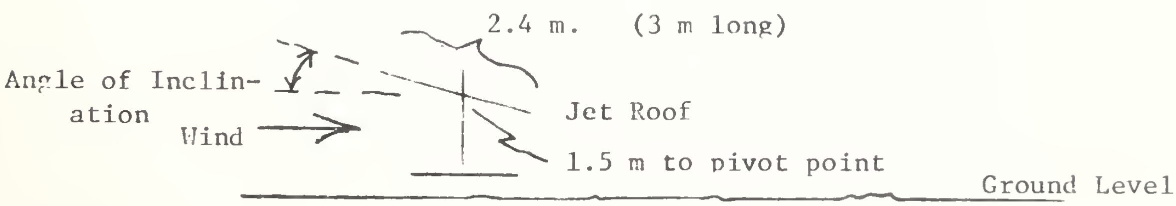

Diagram showing details of experimental jet roof.

TABLE 2. WIND SPEED CHANGES OBSERVED USING LABORATORY MODEL

Inclination of jet roof	Per Cent Change of Wind Speed (full scale equivalent distances) 4.5 m to lee of jet roof	9 m to lee of jet roof
10^{o}	+1.6%	-2%
20^{o}	-8%	11%
30^{o}	-16%	0%
40^{o}	-34%	-5%
50^{o}	-67%	-9%

and 17 percent for roof angles of 30°, 40°, and 50°, respectively. Additional traverses in the downwind direction indicated that the maximum increase did not occur exactly at the trailing edge of the roof but approximately .3 m (full scale) downwind from the trailing edge. The maximum speed could be as much as 30 percent greater than the mean speed at this point, although the increase was maintained only for a very short distance downwind. This relatively large increase in speed at the larger angles of inclination (30°, 40°, and 50°) is a probable explanation for the effectiveness of jet roofs which are inclined at steep angles on correspondingly steep lee slopes. The increased speed in this case does not propagate very far in the downwind direction, but the steep angle of the lee slope makes an extended downwind effect unnecessary.

Although the model studies were by no means comprehensive, the preliminary results do appear to be promising, and it is expected that more information on possible design trends could be gained from further model investigation.

Ridgeline Wind Action. Using the principles learned in the full scale and laboratory model experiments, it is possible to gain some understanding of the jet roof fluid mechanics on a mountain ridge. For greatest wind speed increases, the inclination angle should be between 10° and 20° from the surface wind plane in the downwind direction. Considering the windward plane only, theoretically the most efficient inclination angle would be 20 degrees minus the windward slope angle, assuming that the airflow is parallel to the slope. However, since redirecting the wind is an important function of the jet roof, it is always practical to incline the structure in the lee slope direction. A good rule of thumb is to incline it at approximately the lee slope angle.

On steep lee slopes it is most efficient to incline the jet roof at angles greater than 20^{o}. At angles of 30^{o} and beyond the wind speed increases are marked but do not extend as far downwind. However, as previously mentioned, an extended downwind effect is unnecessary over steep slopes. In this latter case it is desirable to have a steep roof inclination which would prevent accumulation directly adjacent to the jet roof where narrow but dangerous cornices can build.

Climatic Effects. Climate may also be a factor in determining the proper jet roof angle, for climate dictates the nature of the snowfalls and of subsequent cornice growth. For example, during the relatively rare heavy and wet December and January (1967-68) snows in the Bridger Range, only those jet roofs with inclination angles of 15^{o} or less cleared out the cornices over the 30^{o} lee slopes. All other structures with steeper inclinations developed large drifts and secondary cornices, whereas in previous dry snow conditions they had worked satisfactorily. Jet roofs erected over coastal range mountains should probably be inclined to the minimum extent, unless, of course, the lee slopes are very steep.

Other Control Devices. "Kolktafeln" or vertical baffles, with undergaps of 1 m have proven effective in cornice control work, although under most circumstances they are not as effective as jet roofs (Hopf and Bernard, (1963)). Evidently, snow scoured and drifted into a horseshoe shaped mound to the lee of these devices is rapidly age hardened to form a strong unyielding drift if it is not jetted away (Hopf and Bernard, 1963). Further experiments with these baffles are in progress at the Bridger Range because ease of erection would justify their use if cornices can be effectively reduced.

Dry snow jetted to the lee of the standard jet roofs on Bridger Ridge does not accumulate in localized drifts. Snow depths 20 to 30 m to lee of these structures were no different during normal dry snow conditions than in adjacent areas where no jet roofs were emplaced. In the case of wet snows, however, considerable drifting was observed. Snow jetted from cornices by jet roofs can be caught by downwind snow fences, and thus may be utilized to increase the water storage potential at high elevations. It should be noted, however, that such snow fences would have to withstand the standard creep stress of deep snow which amounts to several thousand Kg/m^2 on 30^o slopes.

EFFECT OF RIDGELINE TREES

Distorted low pine and alpine fir along Bridger Ridge have varying effects on cornice accretion along the ridge. Early season lee drifts form adjacent to such trees, but cornice projection is minimized until snow covers the trees after which it can be saltated or rolled up to the ridgeline without disturbance. The cornices formed to the lee of trees are thus usually smaller than cornices formed in adjacent areas where no trees exist. It can be stated, therefore, that trees are somewhat beneficial in preventing cornices, but not totally so.

SNOW FENCING AS A CORNICE PREVENTATIVE

Current experiments with snow fences are under way. An objective is to cause premature drifting to the lee of upwind snow fences, thus "spoiling" the airflow regime necessary for cornice formation. If this is effective, it would provide an economical method of cornice control. A. Roch (pers. comm. 1967) has also suggested that a type of "reverse" jet roof, inclined upwind, would possibly have the same effect; that is, it would spoil the airflow conditions necessary for cornice formation

and thus prevent them. We will also attempt to experiment with this device, although the Swiss have tried it, but without definite results.

ACKNOWLEDGMENTS

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REFERENCES CITED

Hopf, J., and Bernard J. (1963) Windbeeinflussende Bauten in der Lawinenverbauung und - vorbeugung, Mitteilungen der Forstlichen Bundes - Versuchsanstalt Mariabrunn, Heft 60, p. 605-632

in der Gand, H. R. and Zupančič, M. (1965) Snow Gliding and Avalanches, Publication #69, IASH, p. 230-242

Paulke, W. and W. Welzenbach (1928) Schnee, Wächten, Lawinen, Zeitschrift für Gletscherkünde, Band XVI, Heft 112

Seligman, G. (1936) Snow Structure and Ski Fields, (privately reprinted, 1962 by Jos. Adam, Brussels) 555 pages

Welzenbach, W. (1930) Untersuchungen über die Stratigraphie der Schneeablagerungen und die Mechanik der Schneebewegungene nebst Schlussfolgerungen auf die Methoden der Verbauung, Wissenschftliche Veroffentlichungen des Deutschen und Oesterreichischen Alpenvereins, No. 9, Innsbruck